

High Frequency Acoustic Reflection and Transmission in Ocean Sediments

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LONG-TERM GOALS

Development of a physical model of high-frequency acoustic interaction with the ocean floor, including penetration through and reflection from smooth and rough water/sediment interfaces, scattering from the interface roughness and volume heterogeneities and propagation within the sediment. The model will aid in the detection and classification of buried mines and improve SONAR performance in shallow water.

OBJECTIVES

- 1) A comparative study of acoustic sediment interaction models including visco-elastic, Biot, BICSQS, and grain shearing and scattering models including perturbation theory, small slope approximation and finite element models through careful comparison with experimental measurements of the bistatic return, for the purpose of defining the best physical model of high-frequency acoustic interaction with the ocean floor.
- 2) An inversion methodology that can provide input parameters for the resulting physical model from reflection coefficient measurements.
- 3) New finite element modeling capability for acoustic sediment interactions.

APPROACH

Our approach to this problem has three distinct areas of concentration: 1) Participation in at sea tests in collaboration with the NATO Undersea Research Centre, which will further expand our database of in-situ acoustic measurements, 2) Development of a finite element model of scattering from rough interfaces as an aid in understanding difficult physical phenomena that are beyond the capabilities of existing models, and 3) Improving the methodology for the inversion of reflection coefficient data to overcome the effects of propagation and scattering.

WORK COMPLETED

The main achievements of 2008 include:

- 1) Participation in the Measurement and Analysis of the Relationship between the Environment and Synthetic aperture (MARES) sea test which generated reflection and transmission measurements in a nominally flat sandy area over a frequency range from 2 - 80 kHz and an angle range from 5-80 degrees. Data were measured on both isotropic and anisotropic interface roughness.

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14. ABSTRACT Development of a physical model of high-frequency acoustic interaction with the ocean floor, including penetration through and reflection from smooth and rough water/sediment interfaces, scattering from the interface roughness and volume heterogeneities and propagation within the sediment. The model will aid in the detection and classification of buried mines and improve SONAR performance in shallow water.					
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- 2) Preliminary analysis of the MARES data set including magnitude and phase reflection measurements and transmission arrival time structure.
- 3) Development and validation of a Finite Element Model (FEM) to model reflection and bistatic scattering from a rough sediment/water interface that uses interface statistics measured at the EVA and MARES sea tests.
- 4) Continued analysis of the SAX04 data set and its application to ocean propagation models.

MARES Sea test.

The ARL-UT team participated in the MARES from February 24th to March 11th in Biodola Bay, Isola d'Elba, Italy in collaboration with the NATO Undersea Research Center (NURC). Reflection measurements were taken at angles from 5 – 80 degrees grazing and frequencies from 2 – 80 kHz. The reflection coefficient measurement experimental set-up is shown in Figure 1. Four receivers were hung from R/V Leonardo in order to measure a range of reflection coefficients. The depth of the source was varied in order to sweep the angle range. A customized pulse was used to cover the broad frequency range. Seafloor roughness measurements were taken after each reflection measurement using the ROV mounted Laser Profiling System (ROV-LPS). Reflection data were taken at two separate locations on three occasions. Weather events occurred between reflection measurements which significantly altered the roughness of the seafloor allowing for a direct measurement of the effects of seafloor roughness on reflection measurements.

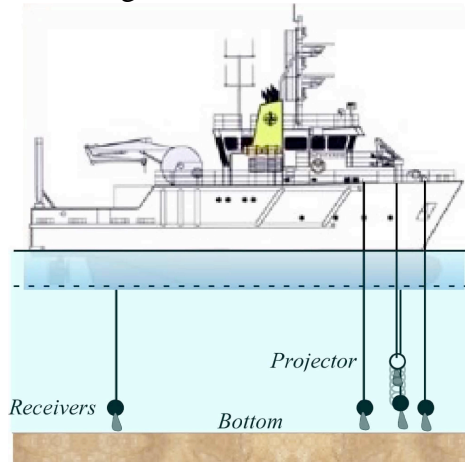


Figure 1: The experimental set-up for the reflection coefficient measurement.

[Four receivers and one source are hung from the R/V Leonardo about 1 meter from the water sediment interface. The source depth is varied to sweep the grazing angle range.]

Along with reflection measurements, the ARL-UT team also made transmission measurements. These measurements were made using a vertical array with four receivers, two of which were inserted into the sediment and two of which were in the water column. A schematic of the experiment is shown in Figure 2. Simultaneous interface roughness measurements were made using the ROV mounted laser profiling system (ROV-LPS). The ROV-LPS projects six red laser lines on the interface by expanding a diode laser beam using a cylindrical lens. A camera is mounted behind the lasers to record the line images. The data are then processed by Dr. Nicholas Chotiros to reveal the interface roughness. (Chotiros, 2007.)

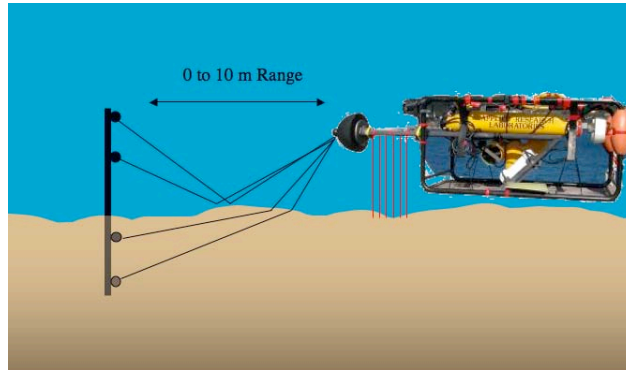


Figure 2: Transmission measurements were taken using a four receiver vertical line array. Simultaneous roughness measurements were taken using the ROV mounted laser profiling system (ROV-LPS).

[Shown is the experimental set up for the transmission measurements at the MARES sea test. The source is 0 to 10 m from the VLA.]

Finite Element Modeling.

The effect of scattering on the reflection coefficient was investigated using finite element modeling. A two dimensional model of seafloor scattering was developed in finite elements using the scattering formulation of the commercial code, COMSOL. An example of the domain used is shown in Figure 3. A Gaussian shaded plane wave is incident on the surface and the pressure on the interface is calculated using finite element analysis. The pressure at a remote point is calculated via the Helmholtz/Kirchhoff integral. Using this method, neither the source nor receiver is in the finite element domain. This drastically reduces the domain size and allows much higher frequencies to be modeled. Also, since the domain is small, this method may allow three dimensional modeling.

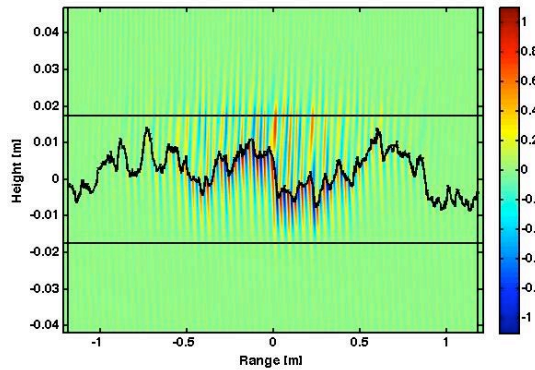


Figure 3: An example of the domain for fluid/fluid scattering using finite element analysis. Note that the x and y axis are scaled differently.

[Shown above is an example of the domain of finite element model for a rough fluid/fluid interface. The pressure is indicated in color on both sides of the interface. Focal points are evident in the upper medium.]

SAX04 Data Analysis

The SAX04 data set was analyzed with respect to its application to propagation in collaboration with Dr. Chotiros. These results, summarized in Dr. Chotiros' annual report, were presented to NAVO

and received positively. NAVO has subsequently provided ARL with data to continue analysis on the effects of sediment variability on propagation.

RESULTS

MARES sea test.

The reflection data were analyzed using a match filter, and the energy reflection coefficient was determined by ratio of the area under the reflected peak to that of the direct path peak. An example of the measured reflection coefficient is shown in Figure 4. The data exhibit strong frequency and angle dependence. These data were used by the NURC team for model verification of target scattering. The data are suitable for inversion. However, the forward model, including dispersive and scattering effects, is still under development.

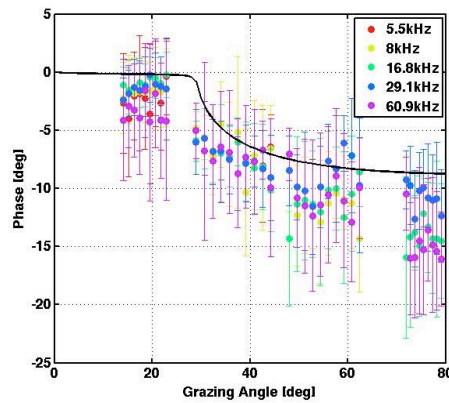


Figure 4: Measured reflection coefficients as a function of frequency and angle from the MARES sea test.

[Shown above are the measured reflection coefficients as a function of angle and frequency. The critical angle at all frequencies is evident. The reflection coefficient decreases as the grazing angle increases. Higher frequencies have lower reflection coefficients.]

The transmission data were analyzed to determine the arrival times. Shown in Figure 5 are the arrival times vs. ping number for two frequencies for an in water receiver (left) and a buried receiver (right). A total of ten frequencies were analyzed. For the in water receiver, the highest ten peaks are shown in different colors. The highest two peaks are shown for the buried receiver. Each ping number corresponds to a different position of the ROV. So for the earliest arrival times, the ROV was closest to the VLA. The position of the ROV may be determined both by the direct path arrival and information from the ROV-LPS and the ROV camera.

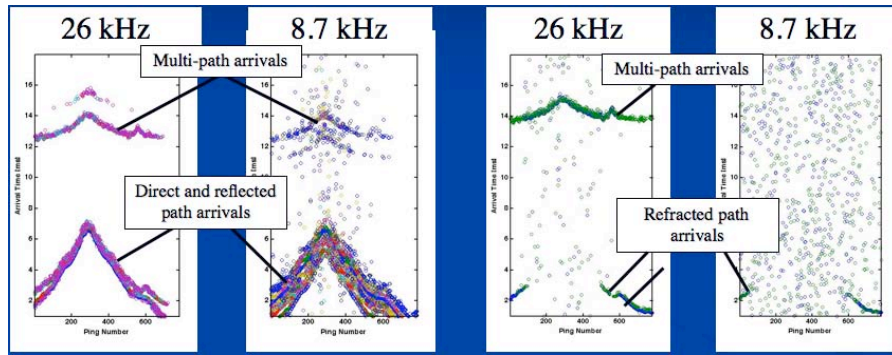


Figure 5: Arrival times on the MARES VLA for receivers in the water column (left) and inserted in the sediment (right). The highest ten peaks are plotted for the in water receivers and the highest two peaks are plotted for the in sediment receivers.

[On the left is shown the time of arrival of the peak of the matched filter pulse for two different frequencies as a function of ping number which corresponds to source location. For high frequencies, four arrivals are evident, the direct path, the sediment reflected path, and two multipaths for the air/water interface. At the lower frequency, there are many more arrivals perhaps corresponding to scattering. On the right is shown the same arrival structure for a buried receiver. Again for most locations, the multipath structure is evident.]

The arrival structure is complicated. For example, for the in water receiver at the higher frequency, there are a clearly defined direct path and reflected path. There is also a corresponding multipath structure from the air water interface. However, there are many other arrivals which may correspond to strong scattering from the interface. At low frequencies, these extra arrivals are more pronounced. At this time, the exact mechanism of the multiple arrival structure is unknown. However, a finite element analysis using the exact interface measured simultaneously with the measurements will be invaluable in determining the effects of strong scattering.

For the buried receiver, the peaks indicate the arrival of the refracted wave. At close ROV distances (short arrival times), the refracted wave arrival is obvious. This corresponds to high grazing angles, above the critical angle of the sediment. As the ROV moves away and the grazing angle decreases, the transmission arrival is not clear. However, this data represents a small fraction of the collected data set. Using finite element analysis and the measured interface conditions, we hope to predict and observe sub-critical transmission in the data and determine its frequency dependence.

Finite Element Model.

A high frequency finite element model of acoustic interaction at the sediment water interface can encompass all of the relevant physical mechanisms including density gradients, rough interface scattering, volume scattering and the scattering from discrete clutter on the interface. However, the first step to an inclusive finite element model is verification with known solutions. For the scattering from a rough interface, there is an exact solution, the Helmholtz/Kirchoff integral and two well known approximations, the Kirchhoff approximation and first order perturbation theory. The finite element was first compared with the three analytic models for a pressure release interface. The roughness on the interface was modeled using the measured power spectrum from the EVA sea test. The results are shown in Figure 6 for a pressure release interface (left) and for a fluid/fluid interface (right). In the figure is shown the mean of the scattering cross section from 100 different surface realizations for a frequency of 10 kHz. The receiver is 300 meters from the interface. The finite element model and the

exact solution are virtually identical for both the pressure release and fluid/fluid models. It is interesting to note the resonances apparent at particular scattering angles such as 122 and 150 degrees for this interface. Although different realizations were used for each model, the resonances are always apparent. The Kirchhoff model is most accurate near specular as expected, while first order perturbation theory provides an accurate description at all scattering angles but specular on the pressure release interface. First order perturbation theory is not compared for the fluid/fluid interface. Therefore, the finite element method has been verified in two dimensions with the exact solution and approximate solutions in the expected regions of validity. The accuracy of the Kirchhoff solution near specular indicates that it may be a viable solution for modeling the reflection coefficient in three dimensions. The Kirchhoff solution, since it neglects most diffraction effects, is a much simpler model and can more easily be converted to three dimensions. The next step for high frequency FEM scattering is to include density gradient and volume inclusions in two dimensions and begin three dimensional interface scattering calculations.

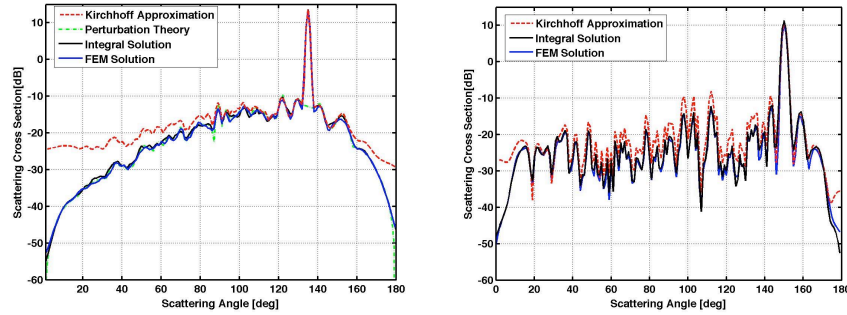


Figure 6: A comparison of the FEM solution with the exact solution, Kirchhoff theory and first order perturbation theory for the measured rough interface from EVA on a pressure release interface (left) and fluid/fluid interface (right).

[Shown on the left is a comparison of the predicted scattering cross section of three analytic models with the finite element model over a range of scattering angles from 0 to 180 degrees.

The finite element and integral solution match at all angles. The Kirchhoff approximation deviates at angles less than 80 degrees and greater than 150 degrees. The perturbation theory solution matches at all angles but specular. On the right is a comparison of the scattering cross section for the integral solution, finite elements and the Kirchhoff solution for a fluid/fluid interface. The finite element and integral solution are identical. The Kirchhoff approximation deviates by as much as 4 dB for all angles but specular.]

IMPACT/APPLICATIONS

All of the current standard acoustic propagation and scattering models that have been accepted and certified by the Navy's Ocean Acoustic Mathematical Library (OAML) approximate the ocean sediment as a visco-elastic medium with a flat interface. This study has identified the effects of a rough interface which predicts significant difference in the mean values of reflection loss at sub-critical angles at higher frequencies. This has impact in long-range propagation models for ASW applications, particularly in littoral environments where the propagation loss is largely controlled by bottom reflection loss. Also, sediment variability, measured in the SAX04 data set, reveals a large change in the measured propagation loss compared to a homogeneous sediment model.

RELATED PROJECTS

This project is closely related to other projects under the ONR “High Frequency Sediment Acoustics” thrust since the environmental inputs required for analysis are dependent on other projects within the thrust. We collaborated with the NATO Undersea Research Center both to perform the MARES and EVA sea tests and results and for information sharing on FEM methods. The finite element scattering method is also being applied to low frequency littoral propagation modeling through an internal ARL research initiative.

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